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An Investigation into the Effects of Material Properties on Shear Wave Velocity in Rocks/Soils

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ABSTRACT: The shear wave velocity (V_s) in the near surface geology has many uses in seismic design including site classification, ground motion prediction equations and evaluation of liquefaction resistance. V_s also allows assessment of rippability, small strain stiffness and verification of soil improvement work. As part of a broader study into site classification for hazard assessment in the United Kingdom, a database of V_s results from around the world was compiled to investigate the effect of different material parameters on V_s. Through statistical analysis, the effect of origin, fracture spacing and weathering state was explored for rock materials tested in both the laboratory and field. The database of soil results was examined to assess the effects of depositional environment. From the dataset analysed, weathering class has the greatest effect; there is a 52% decrease in V_s for rock as the weathering increases from slightly to moderately weathered. The effect of the depositional environment of soils shows that diverse transportation and deposition processes (wind, water, gravity, glacial or in situ) result in different levels of variability in V_s records. This is related to the degree of grading.

1 INTRODUCTION

The shear wave velocity (V_s) of geological materials has become an important input for earthquake seismic design, where it is primarily used to categorise seismic site conditions. Borcherdt *et al.* (1991) showed a correlation between the average shear wave velocity in the top 30m (V_s30) and the amplification of ground motion. This led to the development of site classification schemes based on V_s measurements used worldwide. As part of a project aiming to improve site classification for hazard assessment in low seismicity countries, the effects of geological history on V_s for differing rock types was investigated. This involved:

a) Compilation of a database of V_s values obtained from studies globally, to understand the controlling factors for V_s in different geological units

b) Investigation of the relationships among depositional environment, geological age and other factors with V_s.

2 DATABASE

In order to investigate the influence of various physical properties on V_s, a statistically significant quantity of data was required to be sourced and analysed. Results from site investigations that included both V_s data directly from in situ testing and the corresponding invasive, geological information were obtained from multiple sources and national databases (Table 1). Correlations with standard penetration test (SPT) results were not considered.

These results were then rationalised to account for differences in local/national terminology and classification standards. This was required to ensure consistency between the results. Where this could not be performed (i.e., the reference standard was unavailable), the data was analysed separately, so as not to mix potentially incompatible V_s data.

Each record collected for the database contains a V_s measurement with corresponding depth and a borehole log, providing details of the subsurface materials, ideally including; the material name, USCS classification, structure (bonding, cementation, laminations, stratification), origin (e.g., alluvial, residual, colluvium, aeolian) and geological age. For rock tests, the degree of weathering and fracture spacing was also recorded.

Table 1. Sources of V_s data

Source	Method	No. of sites	No. of records
United Kingdom (Campbell, 2014)	SCPT	60	258
	Crosshole	27	543
	Downhole	14	109
	CSW	1	4
	Refraction	36	72
	PS Logger	7	229
San Francisco Bay (Gibbs *et al.*, 1975, 1977)	Downhole	58	127
LA County and Oxnard-Ventura (Gibbs *et al.*, 1980) (Fumal *et al.*, 1981, 1982b, 1984)	Downhole	84	203
Central California (Fumal *et al.*, 1982a)	Downhole	10	32
Loma Prieta, California (Gibbs *et al.*, 1992, 1993, 1994a)	Downhole	26	172
Turkey (Middle East Technical University, 2014)	MASW	136	1129
Canada (Natural Resources Canada, 2013a, 2013b)	Downhole	20	60
	SCPT	1	4
	Piezoelectric transducer	-	2882
Washington (Cakir & Walsh, 2010, 2011, 2012)	MASW and MAM	67	249
Taiwan (National Centre for Research on Earthquake Engineering & Central Weather Bureau, 2012)	PS Logger	25	306
Bucharest, Romania (Bala *et al.*, 2006, 2007, 2009)	Downhole	21	110
Laboratory database of silicate rocks (Birch, 1960)	Piezoelectric transducer	-	64
TOTAL		593	6553

3 ANALYSIS

The influences of a number of material parameters on V_s values were examined. These included rock type, discontinuity spacing and weathering for rocks and depositional environment for soils. The results are presented as a box and whisker plot, showing the lower quartile, median and upper quartile (box) within the minimum and maximum values (whisker). The average value is also plotted.

3.1 *Origin (rock)*

The database of laboratory tests on rock samples (n=2946) was examined with respect to their identified origin as sedimentary, metamorphic or igneous. The general trend observed was that sedimentary rocks have the lowest V_s, whilst metamorphic rocks have the highest V_s (Figure 1).

The database of in situ V_s results contains 1096 tests in rock, all of which can be primarily classified as sedimentary, metamorphic or igneous. The quality of the rocks varies according to the weathering and fracture spacing which will be addressed in subsequent sections. However initially, the effect of rock origin was investigated (Figure 1).

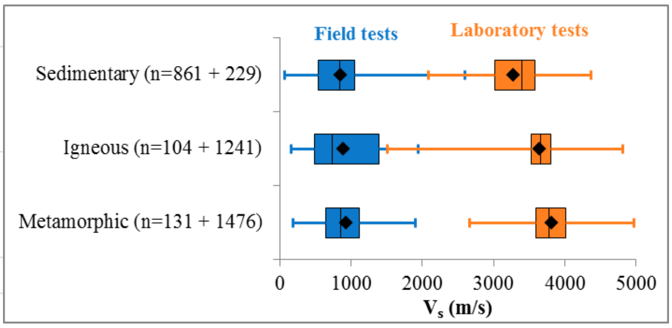

Figure 1. Comparison between field and laboratory V_s results categorized by rock type

The laboratory tests on intact, fresh samples result in higher V_s values compared to tests in the field, with the mean value being 3.8 times higher in sedimentary rock to 4.1 in metamorphic rock. The order of slowest to fastest mean velocity (sedimentary, igneous then metamorphic) is apparent in both data sets, but the magnitude of the increase is larger for the laboratory results.

The reason for discrepancies between the field and laboratory tests is expected to be due to a combination of factors such as accuracy of the test methods, accuracy of material classification (logging), scale effects, boundary conditions, weathering state, confining stress, fracture spacing and anisotropy. Several of these factors will be explored in subsequent sections:

3.2 *Fracture Spacing*

The majority of V_s records which included companion fracture spacing descriptors came from two sources; the Turkish national database and USGS reports (Table 1). The qualitative terms for fracture spacing used in the Turkish logs could not be directly compared with the quantitative categories used in the USGS database, therefore these datasets have been analysed independently, with the Turkish results presented in this paper.

A preliminary analysis of the Turkish data (Figure 2) indicate a possible decrease in V_s as the degree of fracturing increased (i.e., fracture spacing decrease). However two of the six categories do not conform to this trend, namely ‘moderately to slightly jointed’ (n=3) and ‘crushed to highly jointed’ (n=5) materials. This may be due to the fact that these two categories contain the lowest number of records of the six defined fracturing classes. Furthermore, four of the five results in the ‘crushed to highly jointed’ category are identified as Paleozoic aged sandstone, which would be expected to have likely undergone metamorphism and could potentially be a quartzite of much higher strength and therefore velocity than materials typical of sandstone. The effect of geological age was also investigated and it was found that in general, older materials have higher shear wave velocities (N.B., the majority of data in the conforming categories are Cenozoic or Mesozoic in age).

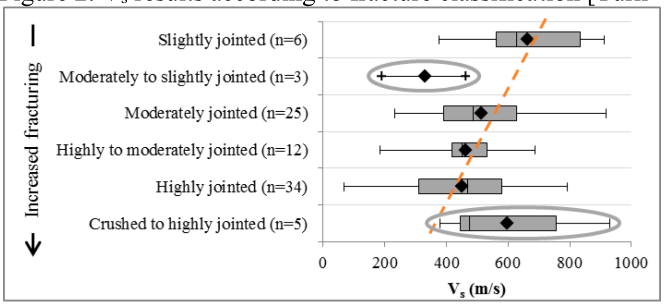

Figure 2. V_s results according to fracture classification [Turkish Data (Middles East Technical University, 2014)]. The linear trend between V_s and fracture density is shown by the dashed line.

3.3 *Weathering*

Within the compiled database 461 V_s measurements are accompanied by a description of the weathering state of rock materials. The highest V_s values, on average, are observed in fresh rock, continually decreasing to the slowest V_s in completely weathered material (Figure 3).

There is a notable change at the moderately to slightly weathered gradational boundary. Less weathered rocks resulted in an average value of approximately 1050m/s whereas the more weathered material was approximately 500m/s (a 52% decrease). The boundary between slightly and moderately weathered, marks the state of weathering where mineral grain decomposition begins, producing some ‘soil like’ material. Overall, soils have a lower velocity than rock, so the decrease observed at this grade is expected.

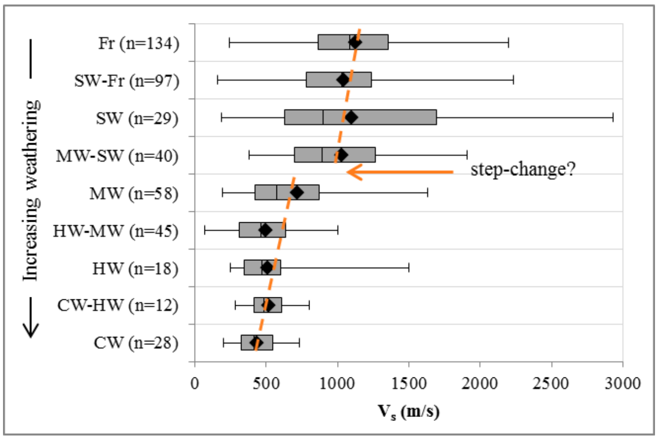

Figure 3. V_S results grouped by weathering category. Dashed line indicates a linear trend between weathering and V_S, with a step-change at the slightly to moderately weathered boundary.

3.4 *Depositional Environment / Origin*

Of the 2471 V_s records for soil, 1954 (79%) contained information relating to the material origin or depositional environment. Although numerous descriptions of origin were provided on the logs and in original reports, these were reviewed and simplified in order that they could be grouped into seven categories (Figure 4).

Residual soils (i.e., weathered in situ from parent rock) show high variability of V_s results with a coefficient of variation (CoV) of 60%. This has been attributed to the dataset covering a range of material types (clay, silty clay, gravelly sand, gravelly clay, etc) and the records also span a number of geological eras (Paleozoic, Mesozoic and Cenozoic).

The least variable data is the aeolian material, having an interquartile range of V_s = 202 - 325m/s and CoV = 33%. This dataset has been compiled from observations made across numerous sites in three countries (Turkey, USA and Romania, Table 1), yet the results remain relatively consistent across all locations. The transportation process (wind) results in selective material sorting, predominantly silt, therefore aeolian data is likely to be the most uniform material in terms of grain size.

Visual inspection of the resultant plot (Figure 4) indicates that all the depositional environments essentially present a similar total range of results (i.e., minimum ~ 100m/s to maximum ~ 1050m/s). The estuarine, alluvial and aeolian environments display similar average V_s values (category 1, V_s = 280m/s), with a second grouping identified for the colluvial, glacial and residual environments (category 2, V_s = 450m/s). The average Category 1 value is 38% less than the Category 2 results.

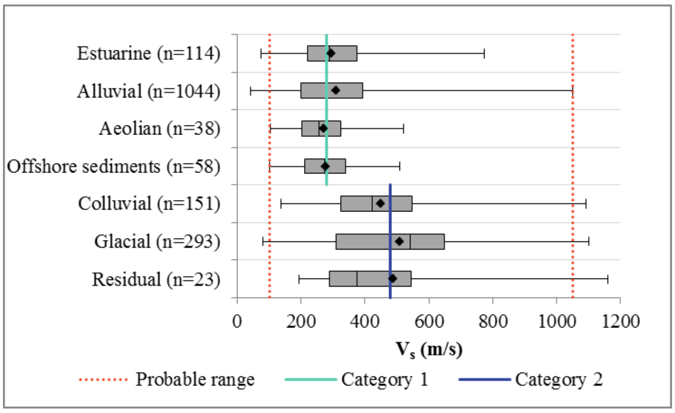

Figure 4. V_s results for soils according to depositional environment

Considering the nature of each of the environment categories, the colluvial, glacial and residual materials (category 2) are most likely to be predominantly well graded as the materials are not sorted during the transportation process. The opposite was expected for the estuarine, alluvial, aeolian and offshore environments, whereby the transportation process (water or wind) would lead to selective transportation and thus sorting of the materials. Wind or water transport would likely result in a comparatively uniform grain size at any particular location. This is in agreement with the observations of Wills *et al.* (2000), who reported that dune sands, basin, lake and beach, deposits have a distinctive (inferred to suggest uniform) grain size distribution, and this material parameter would lead to less variation in V_s values when compared to most bedrock units.

4 CONCLUSION

A global database containing 6531 individual measurements was compiled to examine the influence of various geological characteristics on V_s. This involved the sourcing and assessment of 594 ground investigation site records from 11 different sources. These data allowed statistical analyses of the effects of various parameters on V_s values. Weathering class has the greatest effect; with a 52% decrease in V_s as the weathering increases from slightly to moderately weathered. The effect of the depositional environment of soils shows that diverse transportation and deposition result in different levels of variability in V_s record, related to the degree of grading

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